Clinical outcomes of laser in situ keratomileusis using combined topography and refractive wavefront treatments for myopic astigmatism

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PURPOSE: To evaluate outcomes of laser in situ keratomileusis (LASIK) guided by wavefront alone versus wavefront plus topographic data.

SETTING: NewVision Clinics, Cheltenham, Australia.

METHODS: Twenty-one eyes (14 patients) were distributed into 2 groups in a prospective double-masked study. One group was treated by wavefront parameters alone (WF, n = 11), and the other, by wavefront combined with topography values (WF&VP, n = 10) using vector planning. All treatments were performed using Visx Star S4 CustomVue software. In the WF&VP group, the treatment profile was calculated using simulated keratometry readings from the Humphrey Atlas topography and 2nd-order Zernike coefficients defocus 4 and astigmatism 3 and 5 from the WaveScan wavefront display of the entire eye.

RESULTS: Mean corneal astigmatism preoperatively was 1.07 diopters (D) ± 0.54 (SD) in the WF group and 1.50 ± 0.87 D in the WF&VP group. At 6 months, it was 0.67 ± 0.57 D (39% reduction) and 0.83 ± 0.55 D (44% reduction), respectively. The WF&VP group had a greater reduction in horizontal coma. The mean gain in low-contrast visual acuity under mesopic conditions was 0.06 in the WF group and 0.11 in the WF&VP group and the mean gain in high-contrast visual acuity, 0.02 and 0.05, respectively. Two patients reported a change in the preferred eye postoperatively to the eye treated using vector planning. No result demonstrated statistical significance.

CONCLUSION: The WF&VP group had greater reduction in corneal astigmatism and better visual outcomes under mesopic conditions than the WF group and equivalent higher-order aberrations.

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The inclusion of corneal astigmatism parameters measured using topography or keratometry in the refractive treatment plan was first advocated in 1993[1] and subsequently described in further publications.[2–7] Vector planning incorporates both the measured corneal and refractive astigmatism (2nd-order Zernike 3 and 5) data across the whole ablation profile. Many laser systems incorporate the corneal parameters into the standard treatment by using the average keratometry to minimize spherical aberrations. The overriding principle of vector planning is to approach the goal of corneal sphericity when the orientation of the astigmatism that is being targeted is in a less than favorable orientation, such as oblique or against the rule.[2] A 10-year study[8] that used the technique of vector planning for the treatment of myopic astigmatism in forme fruste and mild keratoconus was recently published.

Differences between the astigmatic parameters measured on the cornea and the refraction are common. The ocular residual astigmatism (ORA), which is the vectorial difference between corneal and refractive astigmatism expressed in diopters (D) and degrees,[2,3,5,8] effectively quantifies this phenomenon. In normal eyes treated for myopic astigmatism, the ORA typically ranges from 0.73 to 0.81 diopter (D).[2,3] In one study,[2] the ORA exceeded 1.00 D in 34% of eyes; in addition, 7% of eyes with the targeted corneal astigmatism exceeded the preoperative magnitude of topographic astigmatism. The ORA can be higher in more irregular corneas such as in those with keratoconus (1.34 D).[8] Approximately one third of eyes with astigmatism have greater than 15 degrees of disagreement between the refractive axis and topographic astigmatic axis,[9] with significantly less refractive astigmatism corrected in these cases ($P = .002$).

To our knowledge, however, no study has been published in which topographic astigmatism and wavefront aberrometry cylinder were combined in

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a systematic treatment paradigm. This study was performed to determine at the least equivalence or a trend in improvement in visual outcomes, with no adverse effects, by incorporating topographic astigmatism values in the surgical treatment plan. This would provide the assurance necessary to produce the results of the vector planning process on a larger scale by expanding the trial to other centers.

Because of the small number of eyes in this study, statistical significance between the 2 groups was not anticipated. In addition, there was an insufficient number of eyes to divide the data into dependent pairs of eyes and independent eyes. Scatter plots were used to display equivalence and trends in data. The number of eyes necessary to gain statistical significance equal to or less than 0.05 was calculated (Appendix 1)[10] using repeated analysis-of-variance measures. This provides a guide to facilitate further studies by other investigators to achieve statistically valid conclusions.

PATIENTS AND METHODS

This prospective double-masked study comprised 21 eyes of 14 patients who were randomly assigned to 1 of 2 groups and treated for myopic astigmatism using the laser in situ keratomileusis (LASIK) technique. All patients had bilateral LASIK; seven patients had bilateral LASIK and 7 patients, unilateral LASIK. The WF group consisted of 6 right eyes and 5 left eyes and the WF&VP group, 6 right eyes and 4 left eyes. One group (WF, n = 11) was treated with treatment profiles obtained from the wavefront aberrometry alone and the other (WF&VP, n = 10), with wavefront aberrometry plus vector planning using the method described by Alpins.[2]

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Dr. Alpins has a financial interest in the ASSORT program used for calculation of the treatment parameters and examination of outcomes. Mr. Stamatelatos is a consultant to ASSORT Pty Ltd.

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AMO/Visx provided the 10 vision keycards required for the combined wavefront and topography values treatment.

Dimitri Chernyak, PhD, and George Dai, PhD, AMO/Visx Inc., set up the treatment profiles for the vector-planning group. Jenny Lee, MSc, BOptom, designed the protocol and analysis of the patient questionnaire. Gemma Walsh, BOptom, provided surgical assistance and implementation of the treatment profiles. James Ong, BSc Optom, PhD and Felicity Allen, PhD provided statistical analyses.

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The odd number of eyes in 1 group occurred because 1 eye of the last patient recruited into the study was used as 20th eye and both the patient's eyes met the inclusion requirements. The study was in compliance with the principles of the 1964 Helsinki Declaration.

The refraction calculated from the WaveScan wavefront aberrometry (Visx) of the entire eye represents the 2nd-order spherocylindrical parameters (defocus 4, astigmatism 3, and astigmatism 5 Zernike polynomial terms). The treatment profile in the WF&VP group was modified in magnitude and direction using vectorial calculations[1,2,5,7,8,11] by the Alpins Statistical System for Ophthalmic Refractive surgery Techniques (ASSORT) planning module (Figure 1). Both the modified spherocylindrical parameters and the measured wavefront aberrometry were provided to AMO/Visx to enable the adjustment required to the CustomVue treatment profile in these 2nd-order components; however, the higher-order aberration (HOA) measurements were not specifically modified. The ablation profiles were then returned to NewVision Clinics for treatment of the WF&VP group. The WF group was treated using the ablation profiles obtained from the WaveScan Wavefront aberrometer. Iris registration was used in both groups, and the wavefront map was manually chosen (not automatically recommended by the wavefront instrument) from a minimum of 3 acquisitions. The choice of wavefront map was based on the quality of the WaveScan image accompanying the treatment, which had to be in focus and well centered, have minimal eyelid/eyelash occlusions, and match the manifest refraction within ±0.75 D for sphere, ±0.50 D for cylinder, and 15 degrees for axis (as recommended by the aberrometer's manufacturers). The topography data used were the measured simulated keratometry from an acquisition on which the data were not distorted by lid drooping, an unstable tear film, or both.

The treatment in the WF&VP group was set to leave 60% of the ORA corrected on the cornea (instead of the customary 100%) and 40% in the wavefront refraction 2nd-order component (instead of the customary 0%). This percentage was based on a calculated average optimized distribution in a previous study[8] of the treatment of myopic astigmatism in patients with forme fruste or mild keratoconus. This can be extended to normal eyes as the magnitude of the ORA is less in these patients and therefore less challenging with regards to corneal and refractive astigmatism outcomes. The decision to leave this percentage constant for all treatments

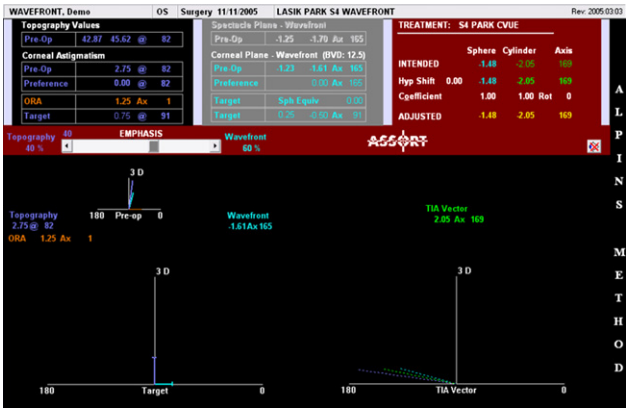

Figure 1. The ASSORT planning screen showing an emphasis of 40% topography and 60% wavefront refraction on the ORA.

was based on creating fewer variables that would influence outcomes between the 2 groups. The WF group had the customary settings based on parameters obtained from the WaveScan Wavefront aberrometry measurements alone. The final theoretical targets for corneal and refractive astigmatism were chosen to ensure that the maximum amount of astigmatism possible for each eye was being treated.[2]

Inclusion criteria consisted of myopic astigmatism, a refractive wavefront cylinder of −1.00 D or greater, an ORA of 0.75 D or greater, and a best corrected visual acuity (BCVA) of 20/30 or better. Cases of form fruste keratoconus, hyperopic or mixed astigmatism, and visually significant cataracts were excluded from the study. Forme fruste and mild keratoconic eyes were identified by criteria outlined in a previous study.[8] These include a superior–inferior keratometric difference of more than 1.50 D on topography, distorted keratometry mires, and a thinner than average cornea (<510 μm) with the thinnest point displaced inferiorly.

Patients who met the inclusion criteria were chosen consecutively and randomized where only 1 eye of a patient was eligible for inclusion. When both eyes were suitable for the study, the eye with the higher ORA was allocated to the WF&VP group and the other to the WF group; this was stipulated by AMO/Visx so the study group would have the greater challenge.

A thorough ophthalmological assessment and examination included a clinical history, uncorrected visual acuity (UCVA) and best corrected visual acuity (BCVA) using the Medmont AT-20R (100 cd/m^2 with manifest and cycloplegic refractions), low-contrast visual acuity (10% contrast, 90% saturation) and high-contrast visual acuity (90% contrast, 10% saturation) using the HiLo contrast chart (NVRI, National Vision Research Institute) at 3 m under photopic (80 cd/m^2) and mesopic (3 cd/m^2) lighting conditions. LogMAR charts were used because the linear scale allows for meaningful interpretation of gains and losses of lines of BCVA.

Contrast acuities were measured with spectacle correction to determine the best potential in each case. Slitlamp microscopy, intraocular pressure, ophthalmoscopy, corneal keratometry (Topcon), topography (Humphrey Atlas), and ultrasonic pachymetry (Pocket II, Quantel Medical) were routinely performed. Preoperative and postoperative examinations were performed using the same contrast chart, aberrometer for wavefront parameters, keratometer, and topographer for simulated keratometry under similar lighting conditions. The treatment mode for the eye(s) was unknown to the patient, surgeon, and examiner.

Bilateral LASIK was performed on the same day in all cases by the same surgeon (N.A.). Before aberrometry measurements, patients were placed in a dark room for approximately 15 minutes. Aberrometry was performed using the WaveScan wavefront system with a minimum of 3 acquisitions, and no eyedrops were used to dilate the pupils. The corneal flaps were created with a nasal hinge using the SiS Amadeus microkeratome (Surgical Instruments Systems, Ltd., AMO) and a nominal 140 μm head. A residual stromal bed of 270 μm or more was left in all eyes. The ablations were performed using the Visx Star S4 excimer laser with CustomVue software. Iris Registration was performed after the corneal flap was lifted in all cases. When Iris Registration was not achieved at first, 2 additional attempts were made. To prevent stromal bed dehydration, iris registration software was not used if capture was not achieved by the third attempt. The optical zone varied from 6.5 to 7.0 mm depending on the pupil size and the ablation required, but it was consistent between the 2 eyes of each patient.

Local anesthetic drops of oxybuprocaine hydrochloride 0.4% (BNX 0.4) were administered. Patients had the option of taking 5 mg diazepam (Valium) preoperatively. Bion Tears 0.4 mL (dextran 0.1% and hydroxy propyl methylcellulose 0.5%) was used as a lubricating agent during the microkeratome pass for each procedure, followed at completion by chloramphenicol 0.5% drops (CPL 0.5) and preservative-free prednisolone sodium phosphate 0.5% drops (PRED 0.5).

Postoperatively, transparent plastic shields were placed over the eyes. The shields were kept in place overnight, removed the next morning, and then applied again over the next 2 nights during sleep. Chloramphenicol 5 mg/mL (Chlorsig) and fluorometholone acetate 1 mg/mL (Flarex) were prescribed 3 times a day for 1 week followed by carmellose sodium 5 mg/mL lubricating drops (Cellufresh) over the subsequent month.

All patients were informed of their inclusion in the study preoperatively but not made aware of which treatment would be applied to their eye(s). Patients for whom both eyes qualified for the study were advised that 1 eye would have wavefront treatment (WF group) and the other wavefront plus vector planning (WF&VP group) but were not informed which treatment each eye received. The treatment paradigms, prepared and administered by the same clinical optometrist (G.S.), were revealed when all 6-month reviews were completed.

Postoperative visits were scheduled for 1 day, and 1, 3, and 6 months. Manifest refraction, UCVA, BCVA, keratometry (excluding day 1), and slitlamp examinations were performed at all visits. Additional tests performed 3 and 6 months postoperatively included corneal topography, wavefront aberrometry (physiological dilation of pupils), and low-contrast visual acuity and high-contrast visual acuity under photopic and mesopic conditions.

To allow accurate comparison of aberrations, all aberrations were standardized to a pupil diameter of 5.0 mm using the Visx RMS Tool software, where RMS stands for root mean square. All postoperative examinations were conducted by the same examining optometrist (G.S).

A subjective questionnaire was given to each patient preoperatively and 1, 3, and 6 months postoperatively. Each participant was asked to rate the degree of glare sensitivity with oncoming headlights while driving at night, problems with halos around lights, driving at night on a sliding 0 to 10 scale, and whether he or she had a preference for 1 eye over the other. The study took 12 months to complete; all surgery was performed between October 2005 and March 2006, with the 6-month follow-up concluding in October 2006.

RESULTS

The mean age of the 14 patients in the study was 34 years (range 22 to 49 years). Seven patients were women, and 7 were men.

Ocular Residual Astigmatism

The mean ORA preoperatively was 1.00 ± 0.16 D (range 0.80 to 1.32 D) in the WF group and 1.06 ± 0.23 D (range 0.77 to 1.18 D) in the WF&VP group (Table 1). Six months postoperatively, the mean ORA was 0.73 ± 0.25 D and 0.82 ± 0.42 D, respectively.

Table 1. Reduction in mean corneal (topography and keratometry) astigmatism 6 months postoperatively.

Astigmatism Reduction (D)	WF Group (n = 11)	WF&VP Group (n=10)
By topography		
Preop, mean ± SD	1.07 ± 0.54	1.50 ± 0.87
Postop 6 mo, mean ± SD	0.67 ± 0.57	0.83 ± 0.55
Simple subtraction	−0.40	−0.67
Change (%)	−39	−44
By keratometry		
Preop, mean ± SD	1.13 ± 0.93	1.49 ± 0.95
Postop 6 mo, mean ± SD	0.75 ± 0.42	0.84 ± 0.50
Simple subtraction	−0.38	−0.65
Change (%)	+9	−34

Corneal Astigmatism

The mean preoperative corneal astigmatism by topography was 1.07 D in the WF group and 1.50 D in the WF&VP group. Six months postoperatively, the mean reduction (calculated from the reduction in each single eye) was 39% (95% confidence interval [CI], −66.89% to −10.56%) in the WF group and 44% (95% CI, −59.38% to −29.02%) in the WF&VP group (Table 1 and Figure 2). The difference in corneal astigmatism reduction was greater between the 2 groups when the percentage reductions by keratometry were used (Table 1).

Refractive Astigmatism

The mean preoperative astigmatism by wavefront refraction (spectacle plane) was −1.71 DC for the WF group and −1.69 DC for the WF&VP group. At 6 months, the mean reduction (calculated from the reduction in each single eye) was 69% in the WF group and 55% reduction in the WF&VP group (Table 2). Individual measurements on a scatterplot (Figure 3) show an overall equivalence between the 2 groups. Similar mean percentage reductions in refractive astigmatism were shown using manifest refraction (Table 2) and were also calculated from the reductions in each single eye.

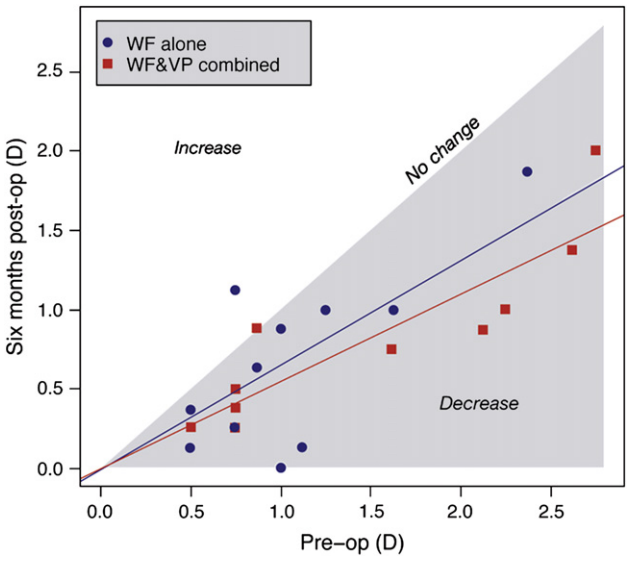

Figure 2. Corneal astigmatism (topography), postoperative versus preoperative. The lines of best fit show a greater reduction in corneal astigmatism in the WF&VP group.

Total Astigmatism (Corneal Plus Refractive)

Using both wavefront and topography parameters, the mean reduction in total astigmatism at 6 months was −1.58 D in the WF group and −1.62 D in the WF&VP group (Table 2). The WF&VP group also had a greater mean reduction in total astigmatism by manifest and keratometry measurements (Table 2).

Visual Outcomes

Preoperative The 2 groups had the same mean BCVA (−0.01 ± 0.03 logMAR, WF group; −0.01 ± 0.06 logMAR, WF&VP group) and very similar low-contrast and high-contrast visual acuities under mesopic and photopic conditions (Table 3A).

Six Months Postoperative The mean gain in low-contrast visual acuity (logMAR) under mesopic conditions was 0.06 in the WF group and 0.11 in the WF&VP group. The mean gain in corrected high-contrast visual

Table 2. Mean reduction in refractive (wavefront and manifest) astigmatism and in total astigmatism (wavefront plus topography and manifest plus keratometry) 6 months postoperatively.

Astigmatism Reduction (D)	WF Group (n = 11)	WF&VP Group (n = 10)
By wavefront refraction (spectacle plane)		
Preop, mean ± SD	−1.71 ± 0.45	−1.69 ± 0.51
Postop 6 mo, mean ± SD	−0.53 ± 0.24	−0.74 ± 0.37
Simple subtraction	−1.18	−0.95
Change (%)	−69	−55
By manfest refraction (spectacle plane)		
Preop, mean ± SD	−1.68 ± 0.55	−1.76 ± 0.70
Postop 6 mo, mean ± SD	−0.43 ± 0.40	−0.68 ± 0.44
Simple subtraction	−1.25	−1.08
Change (%)	−73	−61
Wavefront refraction plus topography		
Postop 6 mo, mean	−1.58	−1.62
Manifest refraction plus keratometry		
Postop 6 mo, mean	−1.63	−1.73

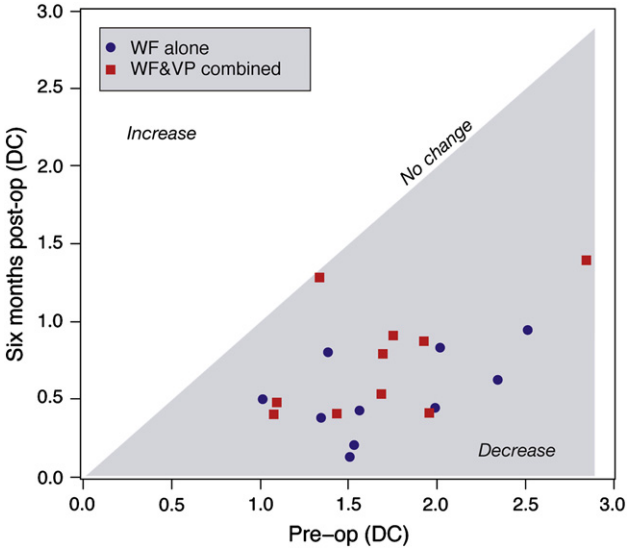

Figure 3. Refractive astigmatism (wavefront–spectacle plane), postoperative versus preoperative.

acuity was 0.02 and 0.05, respectively (Table 3A and Figures 4 and 5). Under photopic conditions, the 2 groups had identical gains.

Gains and Losses in Best Corrected Visual Acuity No eye in the WF group had a gain in BCVA and 2 eyes lost 1 line of BCVA. In the WF&VP group, 2 eyes had a gain of 1 line of BCVA and 1 eye lost 1 line (Table 3B).

Aberrations

All aberrations (Zernike) were standardized to a pupil diameter of 5.0 mm.

Preoperative The mean astigmatism (3) was −0.04 ± 0.54 μm in the WF group and 0.20 ± 0.51 μm in the WF&VP group (Table 4).

Six Months Postoperative Astigmatism (3) and astigmatism (5) were equivalent in the 2 groups (Table 4 and Figures 6 and 7). Horizontal coma increased 0.02 μm in the WF group and decreased 0.04 μm in the WF&VP group. Figure 8 shows a greater trend toward a reduction in horizontal coma in favor of the WF&VP group.

Spherical Equivalent

Table 5 shows the spherical equivalent preoperatively and 6 months postoperatively. At 6 months, both groups were mildly myopic (Table 5).

Astigmatic Vector Analyses

Table 6 shows the mean angle of error (angle between vector of achieved correction and intended correction) 6 months postoperatively. Iris registration capture at time of surgery could not be obtained (after 3 attempts) in 3 eyes in the WF&VP group. This is reflected in the consistently greater angle of error in arithmetic and absolute terms in the WF&VP group than in the WF group.

Table 3A. Visual acuity (corrected, except UCVA) preoperatively and 6 months postoperatively.

Visual Acuity (LogMAR)	WF Group (n = 11)	WF&VP Group (n=10)
Preoperative, Mean ± SD		
BCVA	−0.01 ± 0.03	−0.01 ± 0.06
Photopic		
HCVA	−0.01 ± 0.07	0.00 ± 0.08
LCVA	0.14 ± 0.05	0.14 ± 0.05
Mesopic		
HCVA	0.09 ± 0.08	0.11 ± 0.07
LCVA	0.37 ± 0.10	0.39 ± 0.08
Postoperative 6 mo, mean ± SD (change preop/postop)		
UCVA	0.03 ± 0.06	0.07 ± 0.10
BCVA	0.00 ± 0.03	−0.01 ± 0.04
Photopic		
HCVA	−0.08 ± 0.05 (Gain 0.07)	−0.07 ± 0.05 (Gain 0.07)
LCVA	0.12 ± 0.07 (Gain 0.02)	0.12 ± 0.04 (Gain 0.02)
Mesopic		
HCVA	0.07 ± 0.11 (Gain 0.02)	0.06 ± 0.11 (Gain 0.05)
LCVA	0.31 ± 0.12 (Gain 0.06)	0.28 ± 0.13 (Gain 0.11)

BCVA = best corrected visual acuity; HCVA = high-contrast visual acuity; LCVA = low-contrast visual acuity; UCVA = uncorrected visual acuity

Subjective Responses to Questionnaire

Six months postoperatively, all patients reported fewer glare symptoms during sunlight hours and from headlights at night. Of the 6 patients in the study who had WF treatment in 1 eye and WF&VP treatment in the other, 2 reported a switch after surgery to favor the vision in the eye that had WF&VP treatment. Preoperatively, 1 of these patients had no preference for either eye while the other preferred the eye that had treatment by WF alone. In both patients, this switch in preference can be attributed to better UCVA and lower corneal astigmatism after surgery in the eye that had the WF&VP treatment. No patient transferred preference to the WF alone eye postoperatively.

DISCUSSION

Several studies[12–15] show the advantages of wavefront-customized treatments for refractive error. Using

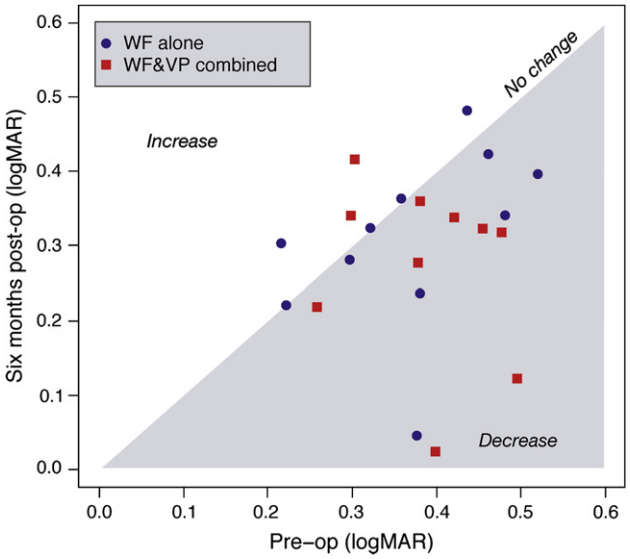

Figure 4. Corrected low-contrast visual acuity under mesopic conditions, postoperative versus preoperative.

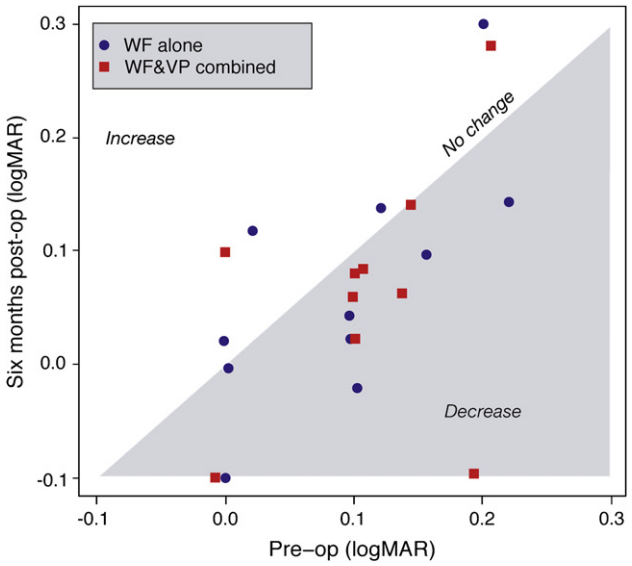

Figure 5. Corrected high-contrast visual acuity under mesopic conditions, postoperative versus preoperative.

wavefront refraction alone in the treatment of astigmatism has been evaluated, and its limitations have been reported.[2,4,5,11,16] These include an excessive amount of residual corneal astigmatism, an increase in corneal irregularity, and no consideration of the patients' conscious perception of their astigmatism.[4]

Treatments guided by topography alone based on spatial analysis of the corneal surface have predominantly been used for corneas that are irregular as a result of previous corneal surgery.[17–21] These treatments have shown to induce higher aberrations compared to preoperative values.[21] To further improve astigmatic outcomes, laser systems are now fitted with iris-registration capabilities and fiducia lines to enhance meridional accuracy of the applied treatment. Despite these advances, the information obtained from topography systems is still primarily used for diagnostic purposes.

Integrating the topography parameters with the wavefront aberrometry in this study was performed in collaboration with AMO/Visx, Inc. Using Iris Registration in both groups reduced the number of variables that might account for differences in outcomes between the 2 groups. The ability to rotate the 2nd-order astigmatism axis independently of the HOAs is not attainable with the standard WaveScan wavefront aberrometry system in conjunction with the Visx Star S4 laser, nor is it currently available in other laser systems to our knowledge. The ASSORT software program modified the spherocylindrical treatment plan to align the treatment closer to the principal meridian of the simulated keratometry of the topography in the WF&VP group. A previous study[8] used this method of vector planning to successfully treat myopic astigmatism in eyes with forme fruste or mild keratoconus. To our knowledge, no previously published study has shown safety and uniformly good refractive and corneal astigmatism outcomes in eyes with regular and irregular astigmatic corneas associated with keratoconus.

Table 3B. Gains and losses in BCVA 6 months postoperatively.

Lines of BCVA Gained or Lost	Number of Eyes	
	WF Group (n = 11)	WF&VP Group (n = 10)
+1	0	2
0	9	7
−1	2	1

BCVA = best corrected visual acuity

Vector planning can be extended to normal astigmatic eyes which, in general, have less amounts of ORA and therefore are less challenging in terms of correcting the total amount of astigmatism (corneal plus refractive) in the optical system. On average, 40% less of the ORA being corrected on the cornea would reduce the corneal astigmatism significantly without compromising the refractive astigmatism outcome.[8] However, any chosen percentage of topography parameters could be incorporated and determined on an individual basis, with the goal of minimizing the remaining total (corneal plus refractive) astigmatism.

There are some limitations to the current technology and the ability to use the vector planning technique to its best advantage. These are as follows:

Table 4. Total and higher order aberrations (Zernike) preoperatively and 6 months postoperatively.

Aberration	Mean RMS (μm) WF Group (n = 11)	WF&VP Group (n = 10)
Preoperative		
RMS Total	2.39 ± 0.54	3.04 ± 1.51
RMS HOA	0.15 ± 0.03	0.15 ± 0.05
Defocus	2.14 ± 0.59	2.81 ± 1.60
Astigmatism 3	−0.04 ± 0.54	0.20 ± 0.51
Astigmatism 5	0.17 ± 0.90	0.17 ± 0.92
Vertical coma	0.06 ± 0.06	0.02 ± 0.07
Horizontal coma	0.00 ± 0.04	0.00 ± 0.06
Trefoil 30	−0.02 ± 0.06	0.03 ± 0.07
Trefoil 0	0.01± 0.06	−0.01 ± 0.06
Secondary astigmatism Z(4,−2)	0.00 ± 0.02	0.00 ± 0.03
Secondary astigmatism Z(4,2)	0.00 ± 0.03	−0.01 ± 0.03
Postop 6 mo		
RMS total	0.58 ± 0.23	0.93 ± 0.78
Change preop to postop, n (%)	−1.81 (76)	−2.11 (69)
RMS HOA	0.22 ± 0.05	0.21 ± 0.04
Change preop to postop, n (%)	+0.07 (47)	+0.06 (40)
Defocus	0.07 ± 0.46	0.33 ± 1.04
Change preop to postop, n (%)	−2.07 (97)	−2.48 (88)
Astigmatism 3	0.09 ± 0.17	0.05 ± 0.26
Change preop to postop, n (%)	+0.13	−0.15
Astigmatism 5	0.04 ± 0.34	0.25 ± 0.41
Change preop to postop, n (%)	−0.13	+0.08
Vertical coma	0.05 ± 0.11	0.04 ± 0.09
Change preop to postop, n (%)	−0.01 (17)	+0.02 (100)
Horizontal coma	0.02 ± 0.08	−0.04 ± 0.08
Change preop to postop, n (%)	+0.02	−0.04
Trefoil 30	−0.04 ± 0.09	−0.01 ± 0.12
Change preop to postop, n (%)	−0.02 (100)	−0.04 (133)
Trefoil 0	0.01 ± 0.07	−0.03 ± 0.08
Change preop to postop, n (%)	0.00 (0)	−0.02 (200)
Secondary astigmatism Z(4,−2)	0.00 ± 0.02	0.00 ± 0.02
Change preop to postop, n (%)	0.00 (0)	0.00 (0)
Secondary astigmatism Z(4,2)	0.00 ± 0.02	−0.01 ± 0.03
Change preop to postop, n (%)	0.00 (0)	0.00 (0)

HOA = higher-order aberration; RMS = root mean square

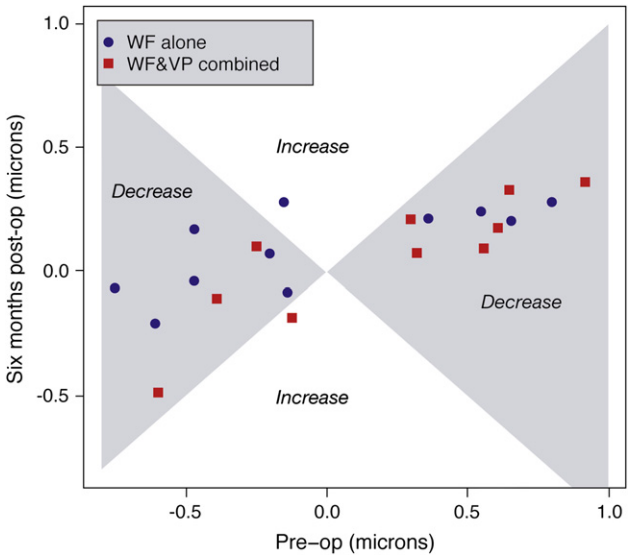

Figure 6. Astigmatism 3 (Zernike), postoperative versus preoperative.

1. Topography systems use simulated keratometry to describe the corneal shape. It is too simple to describe such a complex shape with a single simulated K value; higher-order terms are required in the clinical setting, particularly if they are to be used in the treatment profile.
2. Future advances in technology could allow for the HOAs to change, to reflect the modification occurring when vector planning at the 2nd-order level of the spherocylinder is used.
3. The ability to have a shape profile of the cornea in combination with the corresponding shape profile of the wavefront will maximize the potential of vector planning by repeating the process many times

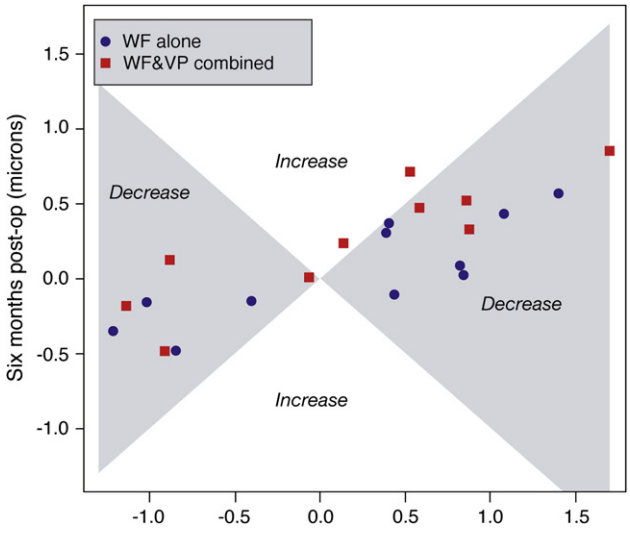

Figure 7. Astigmatism 5 (Zernike), postoperative versus preoperative.

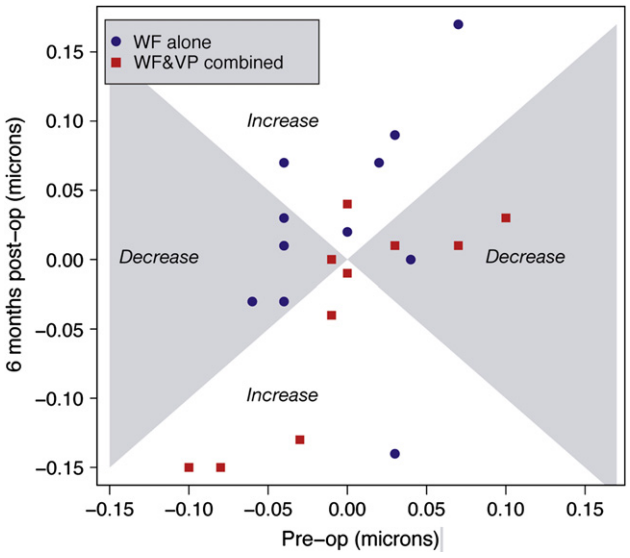

Figure 8. Horizontal coma postoperative versus preoperative displaying a greater trend toward reducing horizontal coma in favor of the WF&VP group.

over the entire ablation profile. At present, the simulated keratometry and the wavefront refraction are the measurements most commonly adopted by surgeons to describe the corneal shape and the optical system of the eye.

4. Variability in measurement in topographic and wavefront devices creates a challenge in obtaining the most consistent numbers from each device. The ORA is calculated using the surgeon-selected preoperative topography and wavefront parameters. Conversion of the wavefront map using different sets of basis functions (eg, Zernike, Taylor) can make wavefront simulation and manipulation easier and more accurate, particularly in cases of irregular corneas.[22–24] The decision as to which are the best representative parameters to use is ultimately made by the surgeon using his or her overall experience. This can be based on variables that include quality of images captured during aberrometry and topography, room illumination, how closely the wavefront refraction corresponds to the manifest refraction, and how the simulated K values of the topography correspond to the corneal keratometry.

Table 5. Spherical equivalent preoperatively and postoperatively.

	Mean SE (D) ± SD (Spectacle Plane)	
Time	WF Group (n = 11)	WF&VP Group (n = 10)
Preop	−2.64 ± 0.77	−3.65 ± 1.82
Postop, 6 mo	−0.10 ± 0.20	−0.26 ± 0.34

SE = spherical equivalent

Table 6. Mean angle of error (absolute) 6 months postoperatively.

	Mean Absolute Angle of Error (Degrees) ± SD	
Time	WF Group (n = 11)	WF&VP Group (n = 10)
Wavefront refraction	5.77 ± 4.35	9.71 ± 10.15
Topography	12.00 ± 9.23	16.61 ± 10.51

5. Vector planning has a less beneficial effect when astigmatism treatment is associated with low ORA or the treatment is for sphere only.

Further studies examining combined topographic–refractive treatment would require individual laser manufacturers to modify the treatment profiles accordingly. The number of eyes treated in this study was restricted to initially display a trend, or at least equivalence, before the study was expanded to pursue trends and significance in the outcome parameters measured. AMO/Visx does not currently have the available resources to further broaden this study. Thus, the results were submitted with the limited number of subjects treated.

Using descriptive statistics,[10] we estimated a cohort of up to 300 eyes necessary to show statistical significance of 0.05 or less in the corneal topography and wavefront refractive astigmatism parameters measured. The process of vector planning reduces corneal astigmatism to a greater degree than treating using refractive parameters alone (Table 1).[8] Thus, the number of eyes required to achieve statistical significance was based on both the corneal topography and the wavefront refractive astigmatism. This statistical significance may readily be achieved in a concurrent multicenter masked randomized study using the vector planning technique[2] incorporated into wavefront-guided treatments. Equivalence was achieved in all measured parameters, and there were some discernible trends in this study that are worthy of reporting, even with the relatively small number of eyes studied.

The WF&VP group had a greater absolute and proportional reduction in astigmatism as measured by both topography and keratometry, despite disadvantages detailed below. This outcome was expected as the corneal astigmatism was incorporated into the treatment plan; thus, the ablation was orientated with less "off-axis" effect to the principal corneal meridian. Figure 2 shows a trend toward a greater reduction in corneal astigmatism (via topography) in the WF&VP group than in the WF group.

The wavefront refraction in the WaveScan wavefront aberrometer is calculated from Zernike

coefficients c_2^-2, c_2^0, and c_2^2, which is universal for all aberrometers.[25] The mean postoperative refractive astigmatism at 6 months was less in the WF group. However, Figure 3 shows a relative equivalence in the 2 groups. The WF&VP group had a greater reduction than the WF group in overall astigmatism (corneal plus refractive) for wavefront and topography parameters 6 months postoperatively. This was also consistent for manifest refraction and keratometry values (Table 2).

Visual outcomes were comparable or better under mesopic conditions (low and high contrast), with a greater potential for improvement in BCVA in the WF&VP group (Tables 3A and 3B).

The HOAs were not specifically modified in either of the 2 groups. However, in practice, they cannot be treated fully independently of the modified 2nd-order term.

The horizontal coma data showed a greater trend in favor of the WF&VP group postoperatively to aggregate around zero microns and remained in the same form as preoperatively; that is, myopic coma or hyperopic coma.

It is interesting that as a result of the questionnaire, 2 patients changed their preferred eye and favored the eye that had WF&VP combined treatment after the surgery. No patient changed preference to the eye treated using WF alone.

Comparative disadvantages of wavefront and vector planning combined (WF&VP group) in this study were as follows:

1. The WF&VP group was expected to have more total astigmatism remaining in the eye and its optical correction postoperatively because the eye with the higher ORA was allocated to this group when both eyes were suitable for inclusion.
2. The WF group had less preoperative corneal astigmatism.
3. The WF&VP group also had greater total RMS values and higher spherical refractive error preoperatively.
4. The 3 eyes in which iris-registration capture failed at time of surgery (after 3 attempts) were coincidentally all in the WF&VP group. This loss of 14% of cases (3 of 21 eyes) is in line with that in another study using this system and rates quoted by AMO/Visx.[26] Light-colored eyes and limbal recognition are possible reasons that iris registration could not be obtained in these cases. The angle of error, described specifically as the angle between the surgically induced astigmatism vector (SIA) and the target induced astigmatism vector (TIA),[1,3] in these 3 cases was not outside the mean distribution in this study; hence, these eyes were included in the analysis.
5. The treatment emphasis for eliminating remaining ORA was fixed to leave 60% on the cornea and 40% in the wavefront refraction to maintain a consistent paradigm for such a study. Individualizing this emphasis choice would have provided more scope for achieving improved outcomes.

Without these disadvantages prevailing in the WF&VP group, a future study incorporating a larger cohort should show an even more favorable trend than obtained in this study in terms of the outcomes of the combined treatment.

Future advances in the measurement of corneal shape and a better understanding of HOAs and their impact on visual function may result in more accurate parameters than are currently used to plan treatments in laser surgery. If the corneal shape is described in greater detail than the simulated K values and aberrometry is displayed by corresponding detail over the entrance pupil, vector planning can be incorporated at each of these coinciding points individually to achieve a true use of combined corneal and wavefront parameters.

In summary, there was a trend toward greater correction of corneal astigmatism, comparable or better visual outcomes (low and high contrast) under mesopic conditions, greater reduction in horizontal coma, and greater potential for improvement in BCVA in the WF&VP group. The outcome benefit achievable was limited by the evident differences in preoperative corneal astigmatism and RMS total magnitudes between the 2 groups, with the WF&VP group starting with the disadvantage of higher levels for both parameters. A future study would likely be impartially randomized, avoiding the bias introduced when the eye with the greater ORA was assigned to the WF&VP group. However, the outcomes in the study group (WF&VP) appeared to have overcome these additional hurdles and achieved equivalent or superior results with no adverse effects.

In conclusion, the application of the detailed information obtained from both wavefront aberrometry and topography systems into a systematic treatment paradigm using vector planning can provide the refractive laser surgeon with a technique to potentially improve corneal and visual outcomes and overall patient satisfaction. This study found measurable benefits by applying the wavefront 2nd-order cylindrical treatment closer to the principal (flat) corneal meridian. Larger studies can now be performed with confidence because the safety and potential benefit of this technique have been established. These would allow rigorous statistical investigation of improvement in visual outcomes gained by combining wavefront with topographic data. The adoption of vector planning

technology for refractive lasers achieves the integration of topographic and wavefront data in a systematic treatment paradigm to further approach the ideal treatment profile.

APPENDIX 1

Calculation for number of eyes required to achieve statistical significance.[10]

$$\text{sample size} = c^2/\delta^2 \left(z_{1-\alpha}\sigma_0 + z_{1-\beta}\sigma_A\right)^2$$

where c is 1; δ is the treatment effect 5, corresponding to the 5% minimal difference (whether the observed effect is a true one); $z_{1-\alpha}$ is the standard normal deviate corresponding to a 5% 1-sided significance level *P* value; $z_{1-\beta}$ is the standard normal deviate corresponding to an 20% error rate (the probability that a true difference has not been missed); σ_0 is the standard deviation under the null hypothesis; σ_A is the standard deviation under the alternative hypothesis.

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